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A UNIQUE STAR IN THE OUTER HALO OF THE MILKY WAY *

DAVID K. LAI[1,2], CONSTANCE M. ROCKOSI[1], MICHAEL BOLTE[1], JENNIFER A. JOHNSON[3], TIMOTHY C. BEERS[4,5], YOUNG SUN LEE[4,5], CARLOS ALLENDE PRIETO [6,7], BRIAN YANNY[8]

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ABSTRACT

As part of a program to measure abundance ratios in stars beyond 15 kpc from the Galactic center, we have discovered a metal-poor star in the outer halo with a unique chemical signature. We originally identified it in the Sloan Extension for Galactic Understanding and Exploration (SEGUE) survey as a distant metal-poor star. We obtained a follow-up spectrum using the Echellette Spectrograph and Imager (ESI) at the Keck 2 telescope, and measure [Fe/H] = –3.17, [Mg/Fe] =–0.10 and [Ca/Fe] = +1.11. This is one of the largest over-abundances of Ca measured in any star to date; the extremely low value of [Mg/Ca]=–1.21 is entirely unique. To have found such an unusual star in our small sample of 27 targets suggests that there may be previously unobserved classes of stars yet to be found in situ in the Galactic halo.

Subject headings: stars: abundances — stars: Population II — supernovae: Galaxy — halo

1. INTRODUCTION

The uniformity of certain abundance ratios in metal-poor stars has been proven to be striking (e.g., Cayrel et al. 2004; Cohen et al. 2004; Arnone et al. 2005; Barklem et al. 2005; Lai et al. 2008). This uniformity is particularly evident in the α-element abundance ratios, indicating some combination of a well-mixed interstellar medium (ISM) and common star-formation history for nearby halo metal-poor stars. Exceptions exist (e.g., Ivans et al. 2003; Aoki et al. 2007b; Cohen et al. 2007), but these have been rarely seen in surveys to date.

The study of metal-poor stars, however, has been largely confined to the solar neighborhood, and in effect the inner-halo region. Recent work provides conclusive evidence that there is a population of stars at Galactocentric distances greater than 15 kpc with kinematics, stellar density profile and metallicity distribution distinct from that of the inner halo (Carollo et al. 2007). The outer halo exhibits a net retrograde motion and is on average composed of more metal-poor stars than the inner halo. Bell et al. (2008) has found evidence for substructure in this outer-halo region as compared to smooth stellar distribution models. Analysis of nearby stars determined to be members of the outer halo through kinematics (e.g., Roederer 2009) have shown an increased scatter in multiple abundance ratios relative to stars that belong to the inner halo.

The formation of galaxies by hierarchical merging may provide a ready explanation for these observations. Bell et al. (2008) showed that their findings of substructure in the halo compared favorably with the simulations of Bullock & Johnston (2005), which assumed that merging and redistribution of the member stars of satellite galaxies formed the halo. Simulations by De Lucia & Helmi (2008) found a more metal-poor outer halo caused by dynamical friction sending the more massive (and therefore more metal-rich) satellites into the inner halo, leaving the stars of less massive satellites preferentially in the outer halo. Depending on when these later satellites accreted to form the outer halo, they will leave a signature in both the bulk metallicity and α-abundance signature of its stars (Robertson et al. 2005; Font et al. 2006; Johnston et al. 2008). Therefore, by studying stars in the outer halo, we are studying stars from lower mass satellites. An example of one of these possible abundance signatures comes from comparing the abundances of nearby stars with stars in current day dwarf spheroidals. For example, present day dSphs sometimes show lower [α/Fe] ratios relative to nearby disk and halo stars (e.g, Shetrone et al. 2001; Venn et al. 2004).

To quantify changes in the stellar populations at large Galactocentric radius, we have initiated a program to measure the abundances for a large sample of metal-poor stars in the outer halo. Using the Sloan Extension for Galactic Understanding and Exploration (SEGUE) survey to select candidates, and the ESI instrument to obtain more detailed follow-up spectra, we have discovered SDSS J234723.64+010833.4 to have anomalous [Mg/Fe] and [Ca/Fe] abundance ratios, and to be unique (to our knowledge) in its [Mg/Ca] ratio of –1.21.

2. OBSERVATIONS AND REDUCTIONS

As part of the SEGUE survey, low-dispersion spectra have been obtained for ∼240,000 stars, including stars specifically targeted for low metallicity (Yanny et al. 2009). Atmospheric parameters and metallicities are derived from these spectra by the SEGUE Stellar Parameter Pipeline (SSPP; Lee et al.

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[1] UCO/Lick Observatory, Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064; david@ucolick.org, crockosi@ucolick.org bolte@ucolick.org.
[2] NSF Astronomy and Astrophysics Postdoctoral Fellow
[3] Department of Astronomy, Ohio State University, 140 W. 18th Avenue, Columbus, OH 43210; jaj@astronomy.ohio-state.edu.
[4] Department of Physics & Astronomy, CSCE (Center for the Study of Cosmic Evolution), Michigan State University, East Lansing, MI 48824, USA; lee@pa.msu.edu, beers@pa.msu.eduand
[5] JINA (Joint Institute for Nuclear Astrophysics), Michigan State University, East Lansing, MI 48824, USA
[6] McDonald Observatory and Department of Astronomy, The University of Texas, 1 University Station, C1400, Austin, TX 78712-0259, USA; callende@astro.as.utexas.edu
[7] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey RH5 6NT, United Kingdom
[8] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510; yanny@fnal.gov

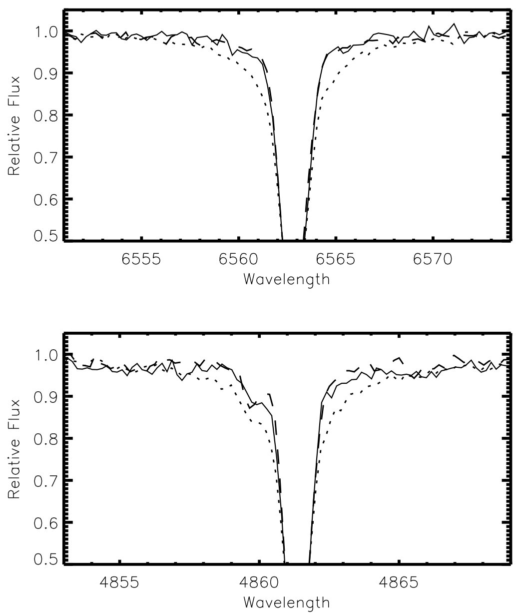

FIG. 1.— The Hα and Hβ lines for SDSS J234723.64+010833.4 (solid line), HD 122563 (long dashed line), and CS 31078-018 (short dashed line). The Balmer lines from HD 122563 give a very good match to those measured in SDSS J234723.64+010833.4.

2008a,b; Allende Prieto et al. 2008). From these stars, we have selected a sample of stars with [Fe/H]$\leq$ –2.0 and Galactocentric distances $\geq$ 15kpc (as determined from the surface gravity estimate) for follow-up observations. For stars, this distant and faint ($V \simeq 16.5$ and greater), a very efficient spectrograph is needed to obtain a reasonable sample size. For this study, we use the ESI spectrometer on Keck 2 (Sheinis et al. 2002). The 0”.75 slit was used, which results in a resolving power of $R \sim 6000$. The efficiency and wavelength coverage of ESI (useable for detailed abundance analysis between $\sim$4000 an 7000 Å) makes this well suited to this study, though the trade-off between efficiency and resolution limits the number of elements that we can measure. It is in this sample that we observed SDSS J234723.64+010833.4.

On 2008 August, 29 (UT) we obtained three 1500 s exposures of SDSS J234723.64+010833.4 (g = 17.23). We achieved a signal-to-noise ratio (S/N) of 40 per pixel at 4170 Å, increasing to 115 per pixel at 6200 Å. The spectra were reduced and extracted using the MAKEE package.[9] Equivalent widths were measured using the SPECTRE program (Fitzpatrick & Sneden 1987). The measured EWs along with line parameters are available upon request (with atomic parameters taken from Lai et al. 2008).

3. STELLAR PARAMETERS AND ANALYSIS

We follow the general treatment outlined in Lai et al. (2004, 2007) to determine the atmospheric parameters and perform the LTE spectral analysis for this star. We have expanded the number of species measured to include Na I and Fe II, and also use a Castelli & Kurucz (2003) model atmosphere with no convective overshooting.

We obtained initial atmospheric parameters of 5108 K for $T_{\rm eff}$, 2.15 for log g, and [Fe/H] = –2.2 from the SSPP. In the course of the analysis we found a large correlation between the excitation potential (EP) and Fe I abundances for individual Fe I lines. We need to adjust the SSPP temperature by approximately –600K to bring this correlation below the 2-σ level. However, this is a large correction and is based on only 16 Fe I lines. As an additional check we compared the Hα and Hβ line profiles to stars with better determined $T_{\rm eff}$ and with ESI spectra from Lai et al. (2004). In Figure 1 we show this comparison to HD 122563 and CS 31078-018, stars with similar $T_{\rm eff}$ to the EP-corrected $T_{\rm eff}$ and SSPP $T_{\rm eff}$ of SDSS J234723.64+010833.4, respectively (Mashonkina et al. 2008; Lai et al. 2008). The SDSS J234723.64+010833.4 Balmer line profiles very closely match those of HD 122563 ($T_{\rm eff}$= 4600K), but are not a good fit to those of CS 31078-018 ($T_{\rm eff}$= 5257K). At present, the origin of this rather large offset in $T_{\rm eff}$ remains unclear, but in examining our larger sample it seems to only be present for some stars with $T_{\rm eff} < 4900K$. The metallicity offset is easier to understand. The high [Ca/Fe] contributes to the offset in [Fe/H] with respect to the SSPP value. Several of the metallicity indicators in the SSPP use the CaII K line strength (Lee et al. 2008a), so the unusually high [Ca/Fe] value would be expected to bias the SSPP-adopted metallicity upward. Combined with the $T_{\rm eff}$ offset, this in large part explains the metallicity difference.

This much lower $T_{\rm eff}$ may also indicate the log g from the SSPP should be changed. Given the similarity to HD 122563 in $T_{\rm eff}$, one reasonable choice is to adopt its log g of 1.5 for SDSS J234723.64+010833.4. As a check on the log g of the star, we compare the Fe I to the Fe II abundance. While we only measure two Fe II lines (at 4583.8 and 4923.93 Å), we find that the Fe I and Fe II abundances agree within reasonable errors using the SSPP atmospheric parameters, but are completely inconsistent when using the lower $T_{\rm eff}$. However, using the log g of HD 122563 for SDSS J234723.64+010833.4 gives a much better agreement between the two species.

We ultimately adopt the $T_{\rm eff}$ of HD 122563, as given in Mashonkina et al. (2008) for SDSS J234723.64+010833.4, motivated by the match in the Hα and Hβ lines of the two stars and minimized EP trend of Fe I lines. We also adopt the log g of HD 122563 predominately because of this $T_{\rm eff}$ match, with the similar abundances of Fe I and Fe II giving confidence to this choice. We then use Equation (7) from Kirby et al. (2008) to derive the microturbulent velocity (v_t), which is based on log g. Our final adopted atmospheric parameters for [Fe/H], $T_{\rm eff}$, log g, and v_t, are –3.2, 4600 K, 1.50, and 1.94 km s^{-1}, respectively. Cross correlating with a radial velocity standard, we measure a heliocentric radial velocity of –225 km s^{-1}.

3.1. *Error estimates*

Although we adopt $T_{\rm eff}$ of 4600 K, motivated both by reducing the EP-abundance trend of Fe I lines and the Balmer line similarity to HD 122563, lowering the $T_{\rm eff}$ by an additional 200 K would even better eliminate the EP-abundance trend in the Fe I lines. We therefore adopt 200 K as the error on $T_{\rm eff}$. We also adopt 0.5 dex as our error on log g, as it is at this level the condition of ionization balance between Fe I and Fe II begins not to be well met (because of the paucity of Fe II lines, we define this to be a difference of 0.3 dex between the two species). While the equation used for v_t gives a good approximation of typical values for a given log g, we can estimate its error based on the trend of abundances given by individual Fe I lines with EWs. The value given by the Kirby et al. (2008) equation yields no obvious trend for individual Fe I abundances with EW. Varying this value by 0.3 km s^{-1} gives a noticeable correlation, leading us to adopt this as

[9] http://spider.ipac.caltech.edu/staff/tab/makee/

TABLE 1
ABUNDANCE SUMMARY

Element Name	[X/Fe]	σ Lines	Number of Lines	Total Error
Fe	–3.17	0.18	16	0.21
FeII	–3.18	0.11	2	0.20
C	–0.28	0.20	···	0.26
Na	–0.23	···	1	0.22
Mg	–0.10	0.24	4	0.15
Ca	1.11	0.09	6	0.08
TiI	0.39	···	1	0.22
TiII	0.57*	0.24	5	0.13
Cr	–0.05	···	1	0.21
SrII	< –0.50*	···	···	···
BaII	< –1.50*	···	···	···
EuII	< –0.50*	···	···	···

* [X/Fe II].

the error on v_t. We estimate the uncertainties from atomic parameters and EW measurements with the standard error of the abundances measured from multiple lines of the same species. When only one line of a certain species is measured, we estimate a conservative error of 0.2 dex due to these factors.

To estimate the final errors on our abundance ratios, we adopt the technique described in Johnson (2002) (Equations (5) and (6)). This includes cross-terms for the dependence of $T_{\rm eff}$ and log g (a decrease of 200K would necessitate a decrease of $\sim$0.3 in log g to maintain reasonable ionization equilibrium) and one taking into account the dependence of v_t with log g.

4. RESULTS

The abundance measurements, number of lines measured for each element, standard deviations of these lines, and final total error estimates are summarized in Table 1. We note that if we used the atmospheric parameters from the SSPP, the abundance ratios would remain essentially the same, but the overall metallicity would be shifted higher to [Fe/H]~ -2.6. In particular, the [Mg/Fe] and [Ca/Fe] ratios are relatively insensitive to changes in the atmospheric parameters.

In Figure 2, we show a Mg and Ca line from our spectrum of SDSS J234723.64+010833.4. We also plot the same lines from a spectrum of HD 122563, which as discussed above should have very similar atmospheric parameters. Even without additional analysis, we can see that SDSS J234723.64+010833.4 is very enhanced in [Ca/Fe] and low in [Mg/Ca] compared to HD 122563. The determination of the Mg abundance comes from the 4703.0, 5172.7, 5183.6, and 5528.4 Å lines, with EWs ranging from 20.1 to 156.9 mÅ.The determination of the Ca abundance comes from the 4226.7, 4425.4, 5588.8, 6122.2, 6162.2, and 6439.1 Å lines, with EWs ranging from 76.9 to 348.5 mÅ. As can be seen in Table 1, the individual lines of Mg and of Ca are in good agreement with each other.

In Figure 3 we plot the [Mg/Fe] and [Ca/Fe] of SDSS J234723.6+010833.4. The [Mg/Fe] is clearly lower than the vast majority of stars; the only stars that show similarly high [Ca/Fe] ratios come from the carbon-enhanced metal poor (CEMP) stars compiled by Aoki et al. (2007a). However, Aoki et al. (2007a) mentions that there are numerous C_2 and CN features in the wavelength range of the Ca lines measured in their highest [Ca/Fe] stars, and that this may be artificially biasing the [Ca/Fe] values high in their CEMP stars. Also, unlike the stars in Aoki et al. (2007a), SDSS J234723.64+010833.4 has a very low carbon abundance, and, as shown in Figure 4, its [Mg/Ca] rato of 1.21 $\pm$0.13 is truly different from other metal-poor stars. This value is 0.5 dex lower then the next lowest star, and would be even more distinct if we ignore the high [Ca/Fe] stars from Aoki et al. (2007a). As discussed further below, most stars that exhibit anomalous α-abundances have similar [Mg/Fe] and [Ca/Fe], or high [Mg/Ca].

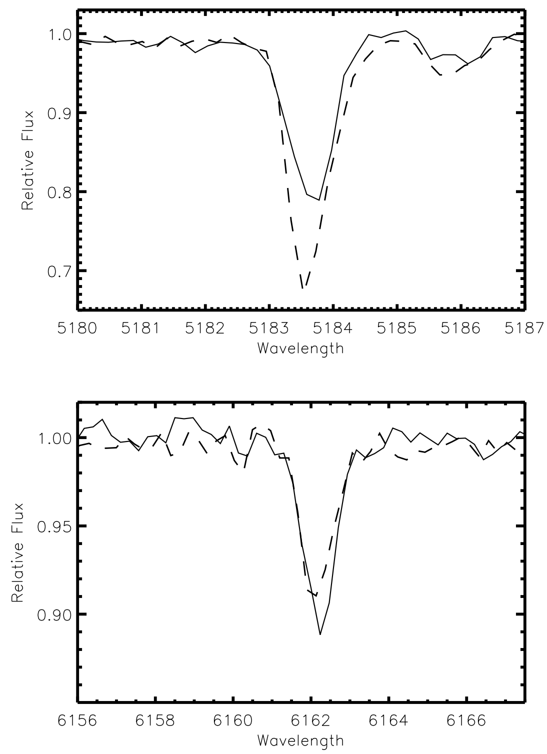

FIG. 2.— A Mg line at 5183 Å(top plot) and a Ca line at 6162 Å(bottom plot) from SDSS J234723.64+010833.4 (solid line), and HD 122563 (long dashed line). HD 122563 has a [Fe/H]= –2.6 and relatively normal [α/Fe]$\sim$ 0.2. SDSS J234723.64+010833.4, which has [Fe/H]= –3.17 should have weaker noticeably weaker lines if this were a typical [α/Fe] enhanced MP star. However, while the Mg is clearly weaker, the Ca line is actually stronger relative to the same line in HD 122563.

5. DISCUSSION

The typical explanation for uniformly low or high α-abundance ratios in a star is that it came from a different stellar formation environment compared to the nearby halo. Specifically, that the time-scale and incidence of SN Ia versus SN II can account for the differences (see, e.g., Figure 1 in McWilliam 1997). This basic explanation can also explain the α deficiencies found in current day dSphs (e.g., Shetrone et al. 2001, 2003; Venn et al. 2004) and high space velocity stars that may belong to the outer halo (Fulbright 2002; Stephens & Boesgaard 2002). While the low [Mg/Fe] of SDSS J234723.64+010833.4 may favor this scenario, the very high [Ca/Fe] suggests that there is much more going on.

On the other end of the scale from SDSS J234723.64+010833.4 are the high [Mg/Ca] stars. These seem to come in two types, stars with high [Mg/Fe] ratios but normal [Ca/Fe] ratios (Aoki et al. 2007b), or low [Ca/Fe] with normal [Mg/Fe] (Cohen et al. 2007). As discussed in Cohen et al. (2007), this behavior may arise because of

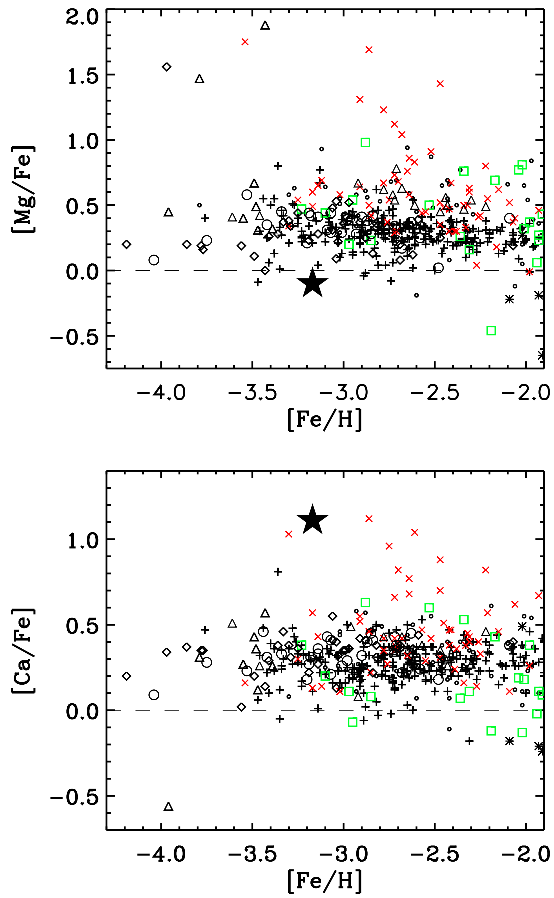

FIG. 3.— [Mg/Fe] and [Ca/Fe] for SDSS J234723.6+010833.4 (the filled star), along with data from multiple other recent studies. Most of the measurements are for nearby halo stars: the large circles are from Lai et al. (2008), the x symbols are from Aoki et al. (2007a,b) and references therein, the diamonds are from Cayrel et al. (2004), the triangles are from Cohen et al. (2008, 2004), the asterisks are from Ivans et al. (2003), the plus signs are from Barklem et al. (2005), and the small circles are from Lai et al. (2004). We have also included abundances measured in dSph galaxies. These are plotted as the squares and come from Frebel et al. (2009); Koch et al. (2008); Fulbright et al. (2004); Shetrone et al. (2003, 2001) (green in the electronic version). The only stars that seem to match the high [Ca/Fe] are the CEMP stars from the study of Aoki et al. (2007a).

the difference in nucleosynthesis mechanisms between Mg and Ca, hydrostatic and explosive α-burning, respectively (Woosley & Weaver 1995). This suggests that in the progenitor(s) of SDSS J234723.6+010833.4, the products of explosive nucleosynthesis dominated the ejecta as compared to the products of hydrostatic burning. Measurements of Si (an explosive α-burning product) and O (a hydrostatic α-burning product) could greatly bolster this argument, however these two elements have transitions that require bluer wavelength coverage and higher-resolution spectra than ESI can provide.

The low [C/Fe] of this star is of particular note. Combined with the low [Ba/Fe] upper limit, this indicates that the atmosphere has not been polluted by a companion that has gone through its asymptotic giant branch (AGB) phase. While it is possible that this star has processed some of its original C to N, and therefore began with a higher original [C/Fe] abundance ratio, it is unlikely that enough C was burned that this star was ever a CEMP star ([C/Fe]>1). However, if somehow a significant portion of its C has been converted to N

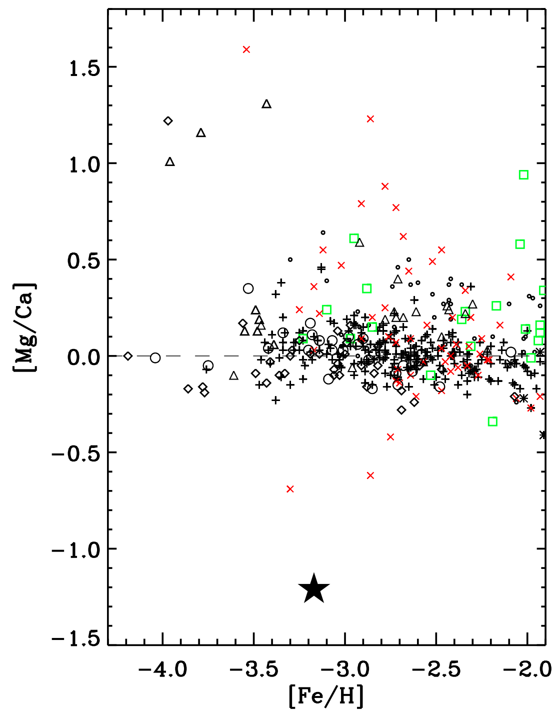

FIG. 4.— In terms of [Mg/Ca], SDSS J234723.64+010833.4 Is unique. The symbols are as in the previous figure. It is clear from this figure that most stars that exhibit anomalous α-abundance ratios have either a normal or high [Mg/Ca], not the very low value exhibited by SDSS J234723.64+010833.4.

internally, then some of its Mg may also have been processed to Al through proton burning in layers with T$\geq 70 \times 10^6$ K. If a mixing event that brought this C-depleted material to the surface was also deep enough to bring some of this Mg-processed material to the surface, then the surface Mg abundance would have been diluted and may partially explain the low observed [Mg/Fe] value. While this is unlikely, in part because field stars do not show a correlation of Mg with Al (e.g., Gratton et al. 2004) and we measure a relatively low [Na/Fe] abundance ratio (which one would expect to be enhanced in this scenario), further observations of this star to determine its Al abundance can determine the validity of this scenario.

If we assume that the low [Mg/Ca] was not the consequence of processed material from a companion or internal to the star itself, then this unique abundance ratio was present in the ISM that originally formed the star. This indicates either a unique SN progenitor or mix of progenitors giving rise to the [Mg/Ca] abundance ratio. There do exist metal-free SN II models that can produce low [Mg/Ca] ratios (Heger & Woosley 2008), and we find that these generally fall in between the 10 and 18 $M_\odot$ range. However, because of the limited number of abundances that can be measured from our spectrum, we are prevented from performing these fits with confidence. Regardless, stars like SDSS J234723.64+010833.4 must be exceedingly rare (at least in the inner halo) given that this is the first such star to display such a ratio. Clearly, this star is not a product of the well-mixed ISM which seems to characterize the inner halo. As such, it is an intriguing candidate for being the product of a single unique progenitor and, combined with its metallicity, makes it a possible true second-generation star (Tumlinson 2006). A more detailed high-resolution analysis of this star is needed before a more definitive statement can be made.

An open question is whether this is a unique star formation environment in the outer halo. Using its estimated surface gravity and measured *g* magnitude applied to the isochrones from Girardi et al. (2004), we estimate that SDSS J234723.64+010833.4 is located approximately 40 kpc from the Galactic center (and $\sim$ 32 kpc below the Galactic plane), well into the outer-halo region as defined from the Carollo et al. (2007) measurements. In addition to the observational evidence of a distinct outer-halo component, simulations have also shown that an inner–outer stellar halo structure will arise assuming the hierarchical merging picture (e.g, De Lucia & Helmi 2008; Bullock & Johnston 2005), with small satellites merging to form the outer halo. This suggests that the outer stellar halo is composed of stars from many different star-formation environments. This possibility is hinted at by the study of Roederer (2009), which finds increasing chemical abundance diversity for stars that have orbits that bring them to the outer-halo region as compared to stars which solely exist in the inner halo.

While this star does not resemble any abundances measured in dSphs to date, in the scenarios described by the studies above it is possible that it once belonged to a system that was accreted into the outer-halo region. The discovery of more anomalous stars like SDSS J234723.64+010833.4 in the outer halo could be a significant step in completing the picture for how the stellar halo formed. It is noteworthy that this star was discovered in a sample of only 27 in situ outer-halo stars. This suggests that, while obviously rare, we may discover additional such stars as we increase our sample of outer halo stars with available detailed abundance measurements.

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